An economical scale-aware PDF-based turbulence closure model

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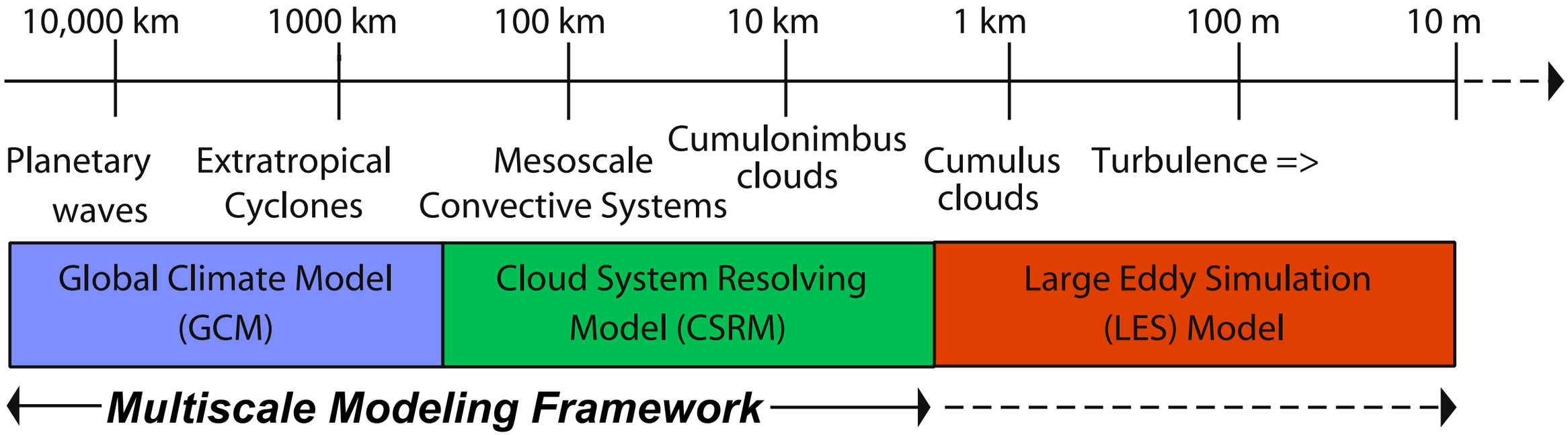
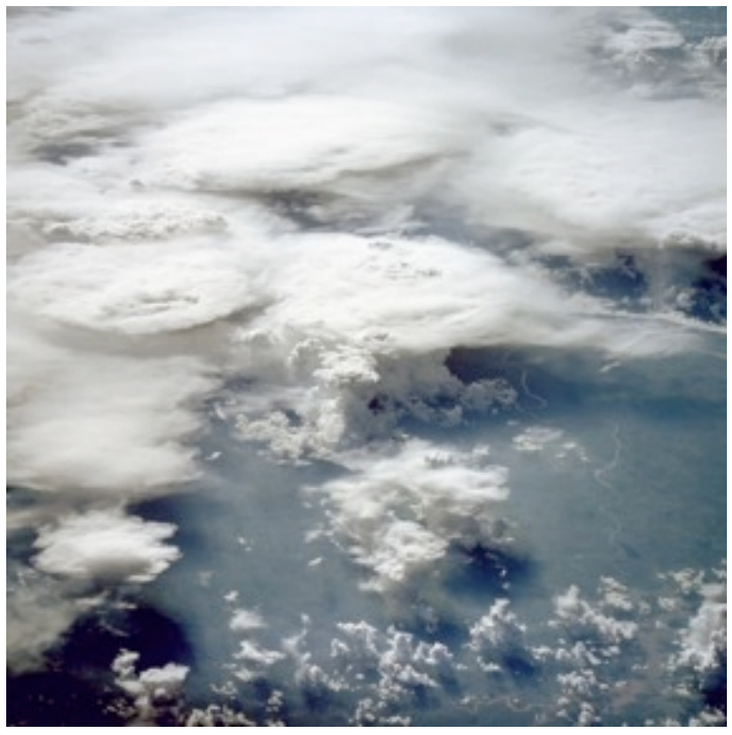
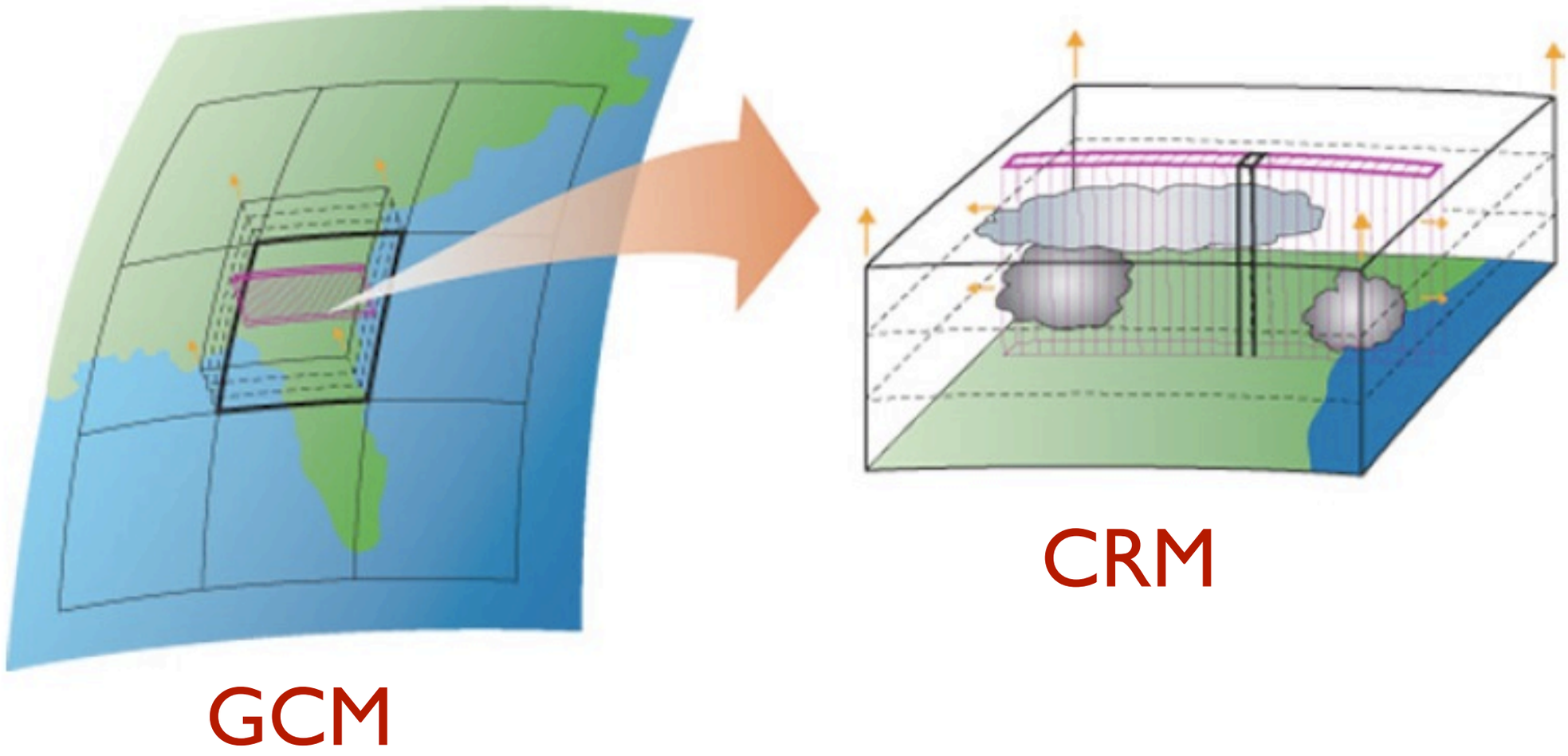
Photo: Lis Cohen

Scales of Atmospheric Motion





Multiscale Modeling Framework



In MMF, a 2D CRM is embedded in each grid column of the GCM.

Community Atmosphere Model (CAM)
+ System for Atmospheric Modeling (SAM)
=> Super-Parameterized CAM (SP-CAM)

SAM was developed by Marat Khairoutdinov (http://rossby.msrc.sunysb.edu/~marat/SAM.html

Boundary layer clouds in cloud-system-resolving models (CSRMs)

- CSRMs may have horizontal grid sizes of 4 km or more.
- Such CSRMs are used in MMF, GCRMs (global CSRMs), and many NWP models.
- In such models, CSRMs are expected to represent all types of cloud systems.
- However, many cloud-scale circulations are not resolved by CSRMs.
- Representations of SGS (subgrid-scale) circulations in CSRMs can be improved.

- One approach for better representing SGS clouds and turbulence is the *Assumed PDF Method*.

- This method parameterizes SGS clouds and turbulence in a unified way.

- It was initially developed for boundary layer clouds and turbulence.

- It is a very promising method for use in coarse-grid CSRMs.

Steps in the Assumed PDF Method

The Assumed PDF Method contains 3 main steps that must be carried out for each grid box and time step:

(1) Prognose means and various higher-order moments.

(2) Use these moments to select a particular PDF member from the assumed functional form.

(3) Use the selected PDF to compute many higher-order terms that need to be closed, e.g. buoyancy flux, cloud fraction, etc.

Our PDF includes several variables

We use a three-dimensional PDF of vertical velocity, w, total water (vapor + liquid) mixing ratio, q_t, and liquid water potential temperature, θ_l :

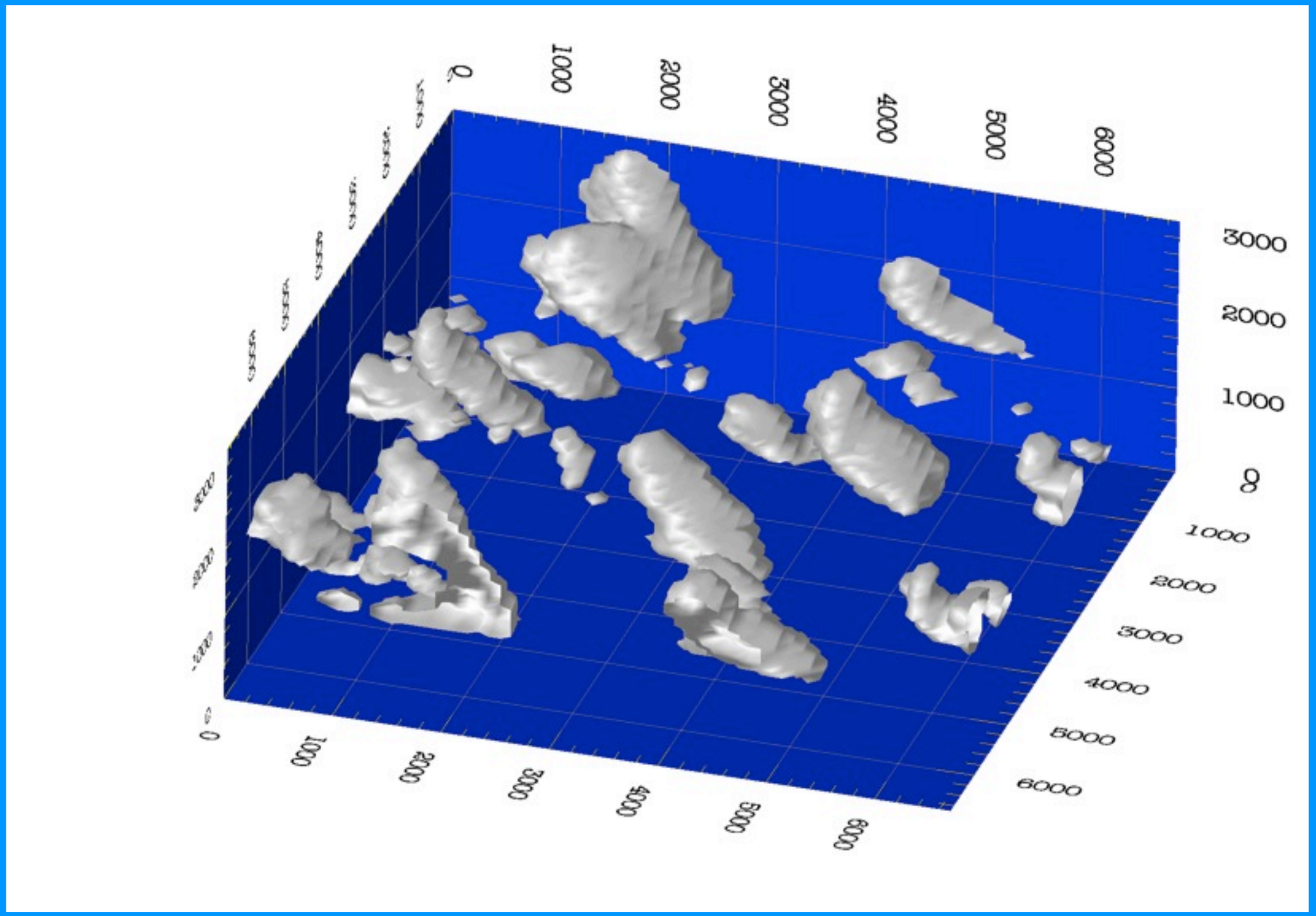
$$P = P(w, q_t, \theta_l)$$

This allows us to couple subgrid interactions of vertical motions and buoyancy.

Randall et al. (1992)

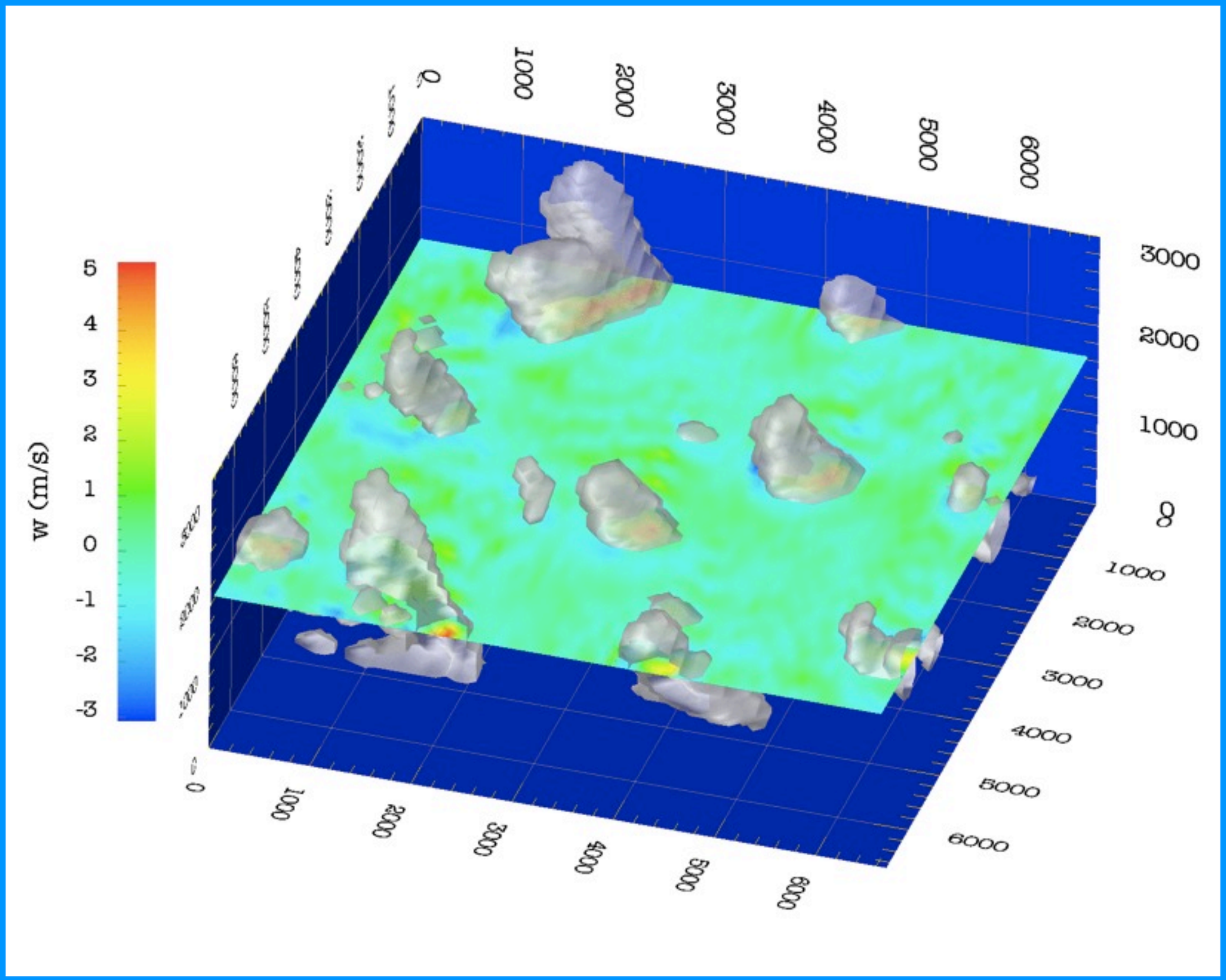
PDFs of cumulus clouds

Isosurface of cloud water: 0.001 (g/kg)



(courtesy of W. R. Cotton & J.-C. Golaz)

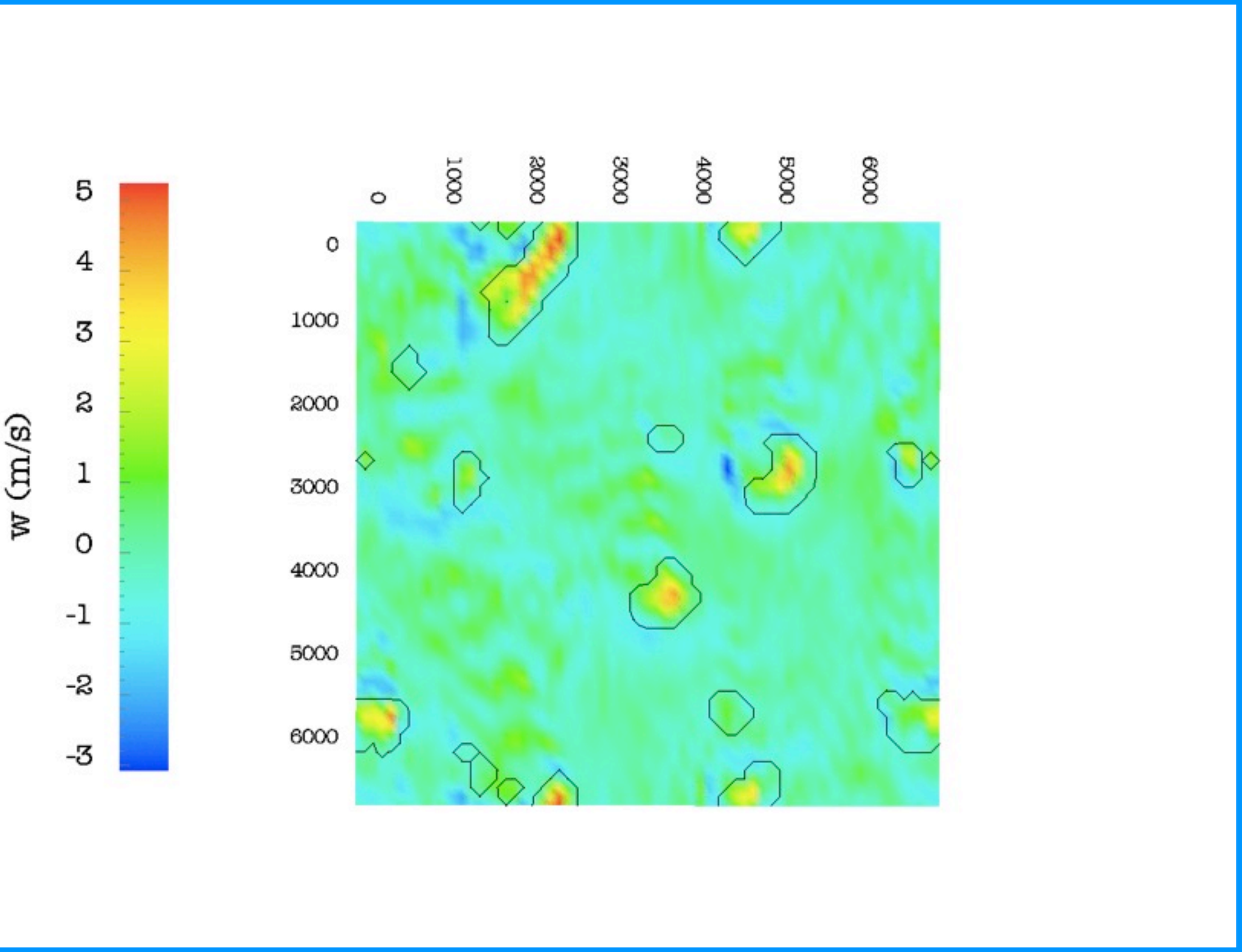
PDFs of cumulus clouds



(courtesy of W. R. Cotton & J.-C. Golaz)

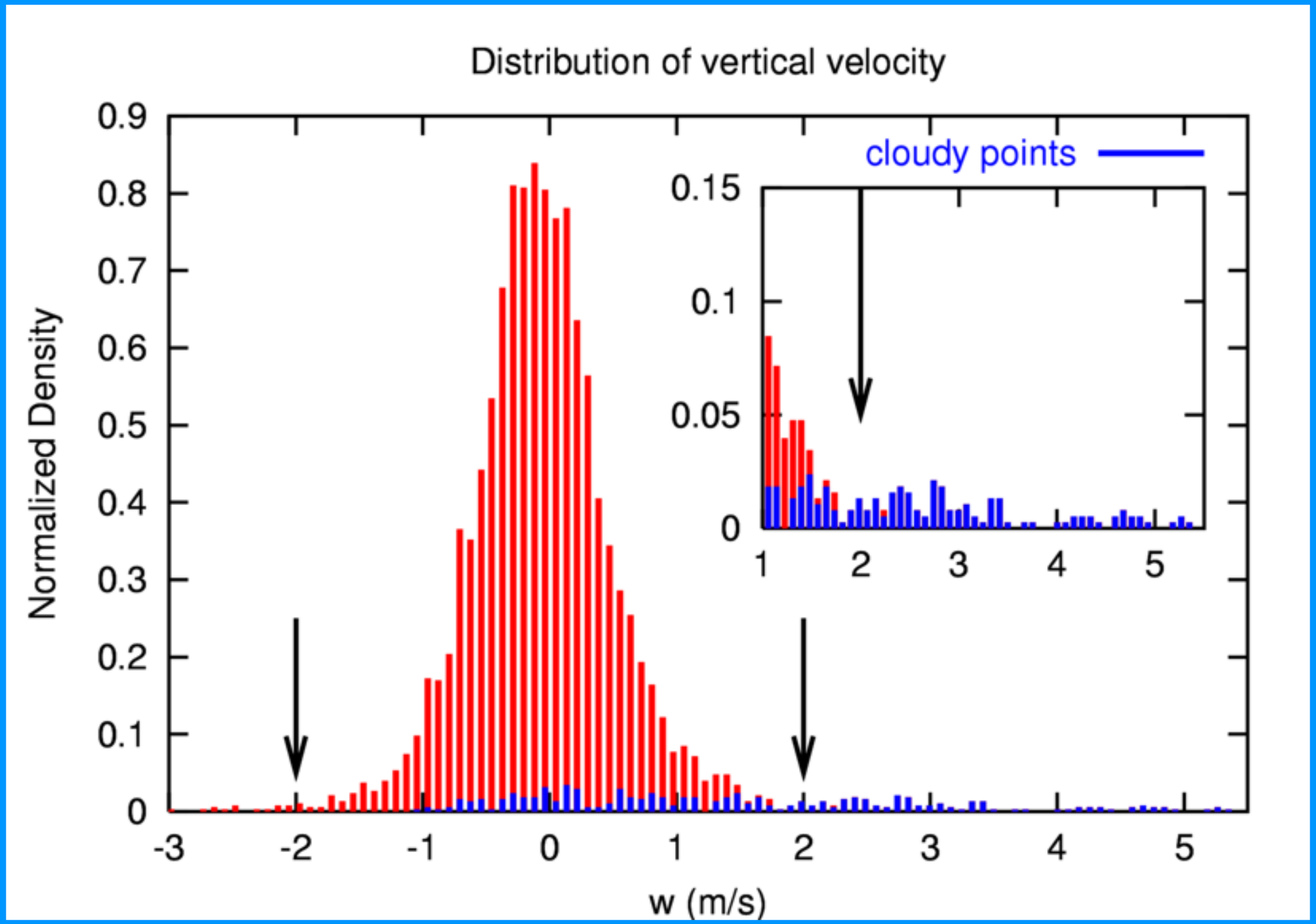
PDFs of cumulus clouds

Horizontal cross section of vertical velocity; z=1680(m)



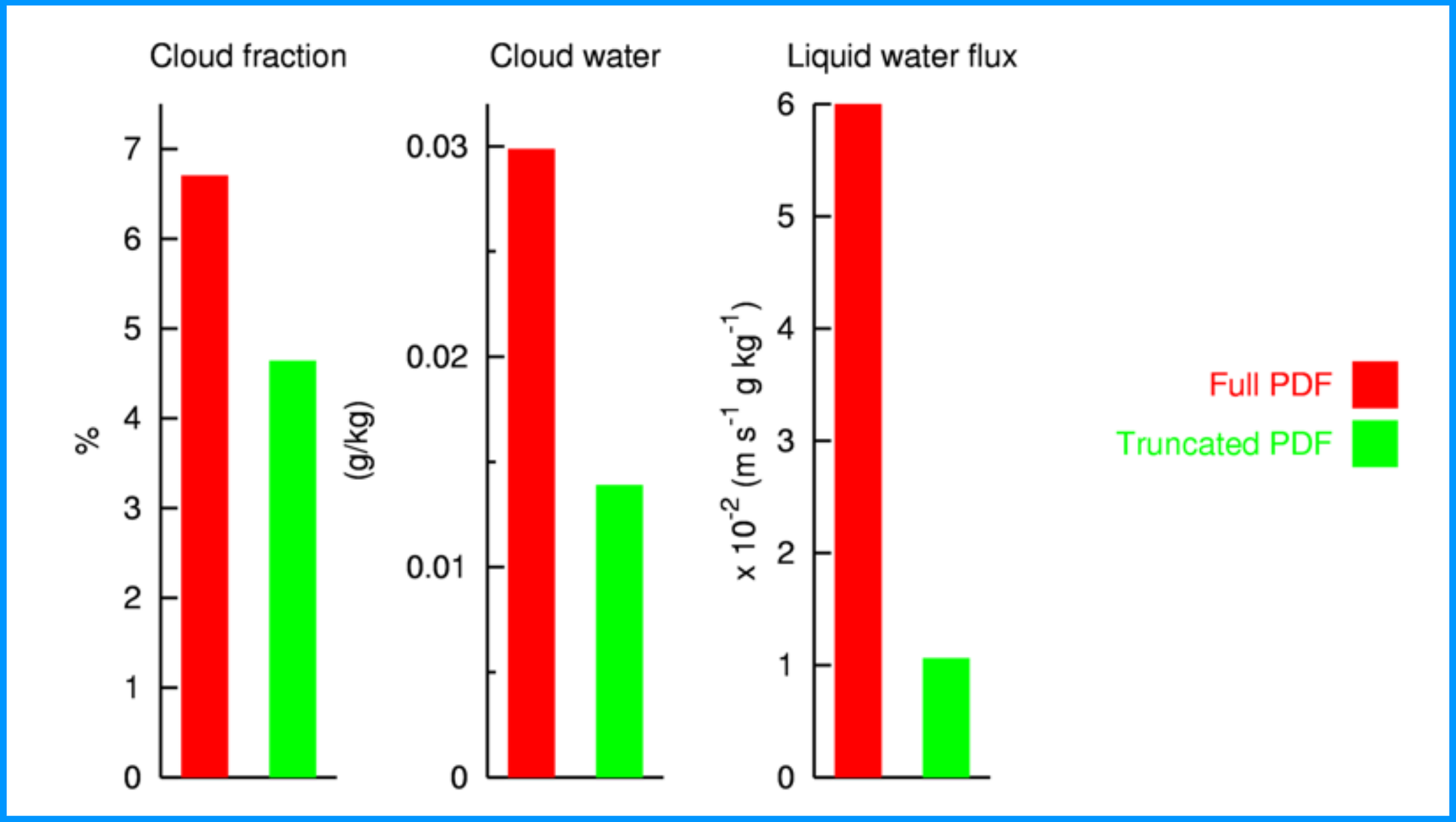
(courtesy of W. R. Cotton & J.-C. Golaz)

PDFs of cumulus clouds



(courtesy of W. R. Cotton & J.-C. Golaz)

PDFs of cumulus clouds

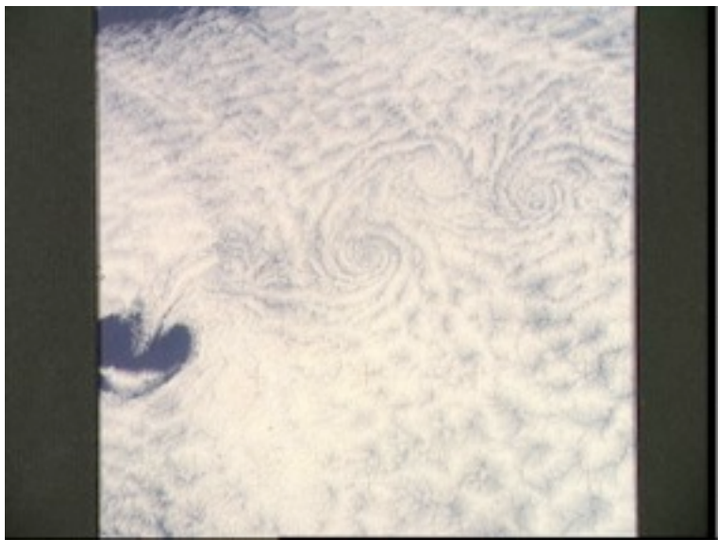


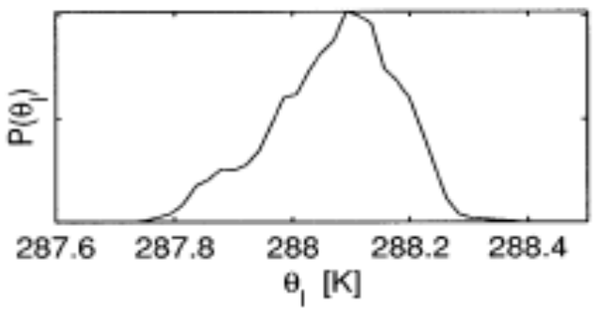
(courtesy of W. R. Cotton & J.-C. Golaz)

Approach

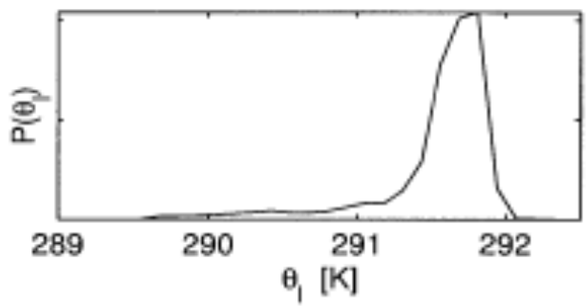
- One major difficulty of the PDF approach is to find a family of PDF that is both:
  - Flexible enough to represent cloud regimes with cloud fraction ranging from a few per cent to overcast.
  - Simple enough to allow analytical integration of moments over the PDF.

Unified Approach to Cloud Representation

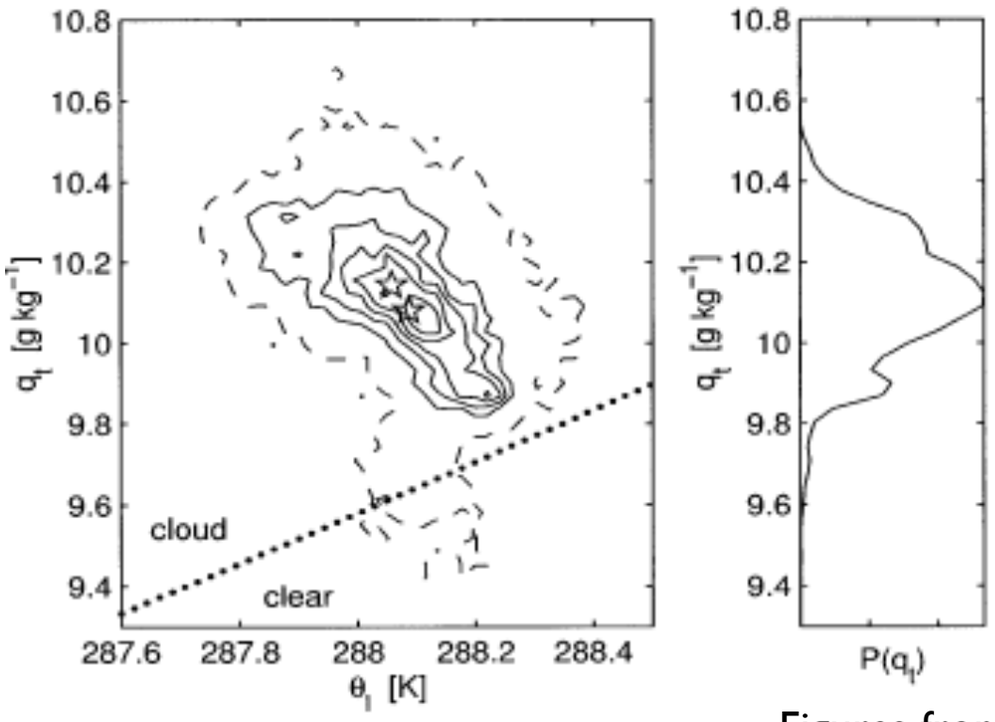


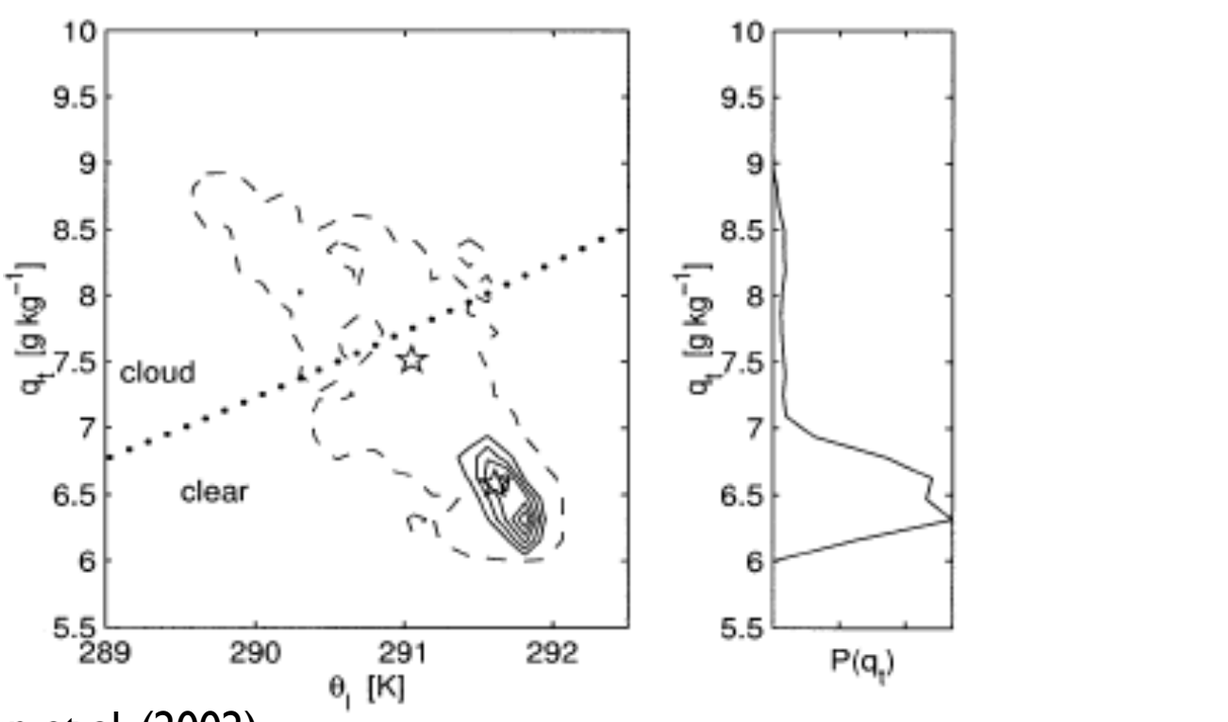


Stratocumulus



Cumulus





Figures from Larson et al. (2002)

Approach

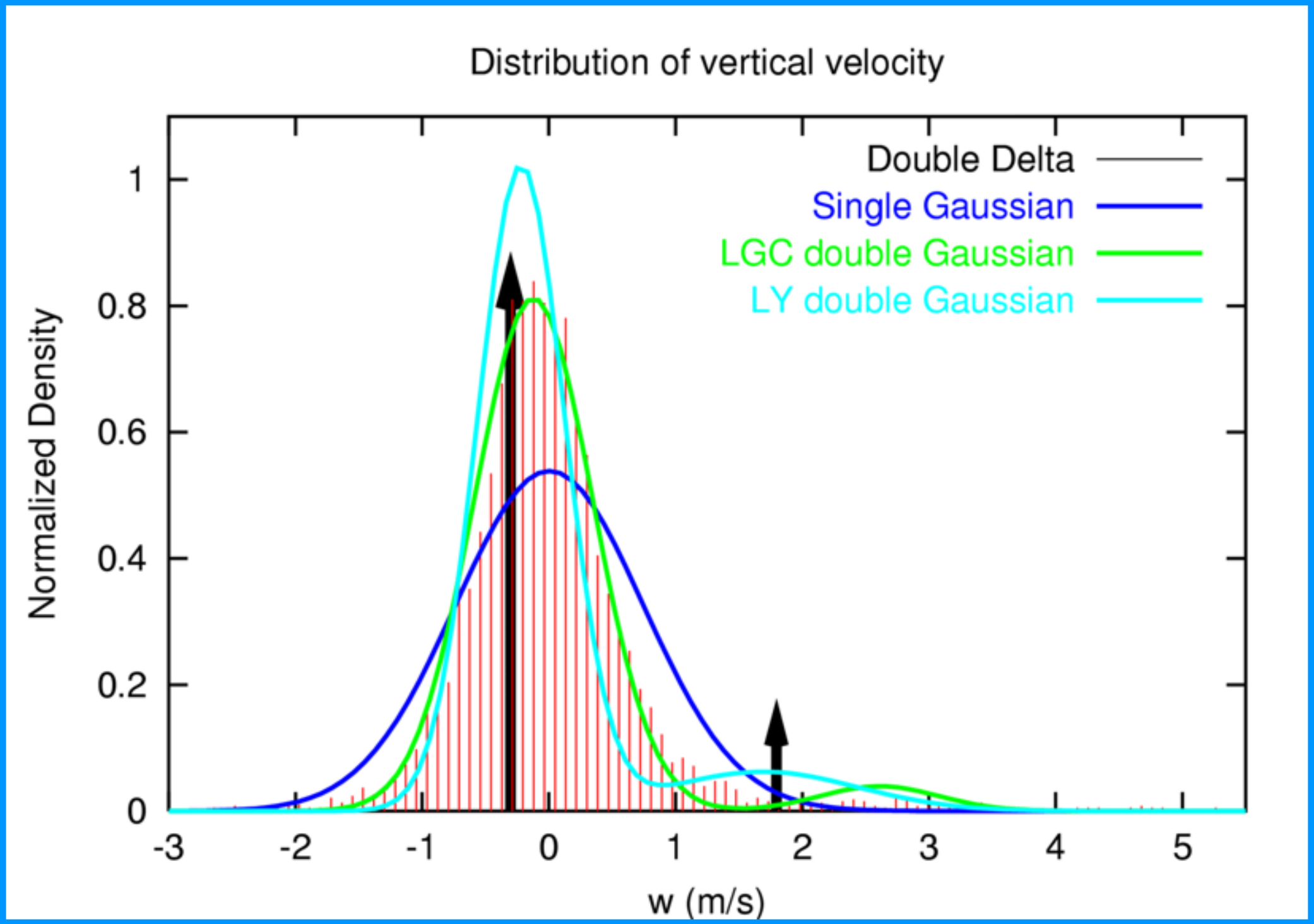
- Examples of families of PDFs that have been proposed in the past include:
  - Single Gaussian distribution to account for subgrid-scale cloud fraction and cloud water (e.g., Sommeria and Deardorff 1977; Mellor 1977).
  - Double Dirac delta function: one delta function to represent the cloudy part of the distribution and the other the environment (e.g., Randall et al. 1992; Lappen and Randall 2001a,b,c).

Fitting PDFs

- Now, let's fit various families of PDFs to the LES data to see how they perform.
- Fit trivariate joint PDFs.
- Test four different families of PDFs:
  - Double Dirac delta functions: 7 parameters (Randall et al. 1992)
  - Single Gaussian: 9 parameters (extension of Sommeria and Deardorff 1977).
  - LGC double Gaussian: 10 parameters (Larson et al. 2002)
  - LY double Gaussian: 12 parameters (Lewellen and Yoh 1993).

(courtesy of W. R. Cotton & J.-C. Golaz)

Example of a PDF fit



(courtesy of W. R. Cotton & J.-C. Golaz)

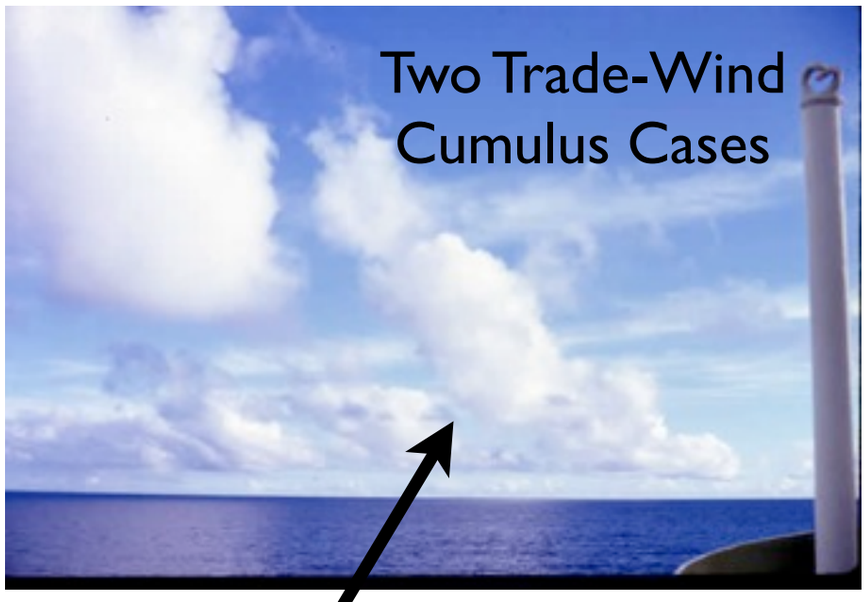
Evaluations of the PDFs

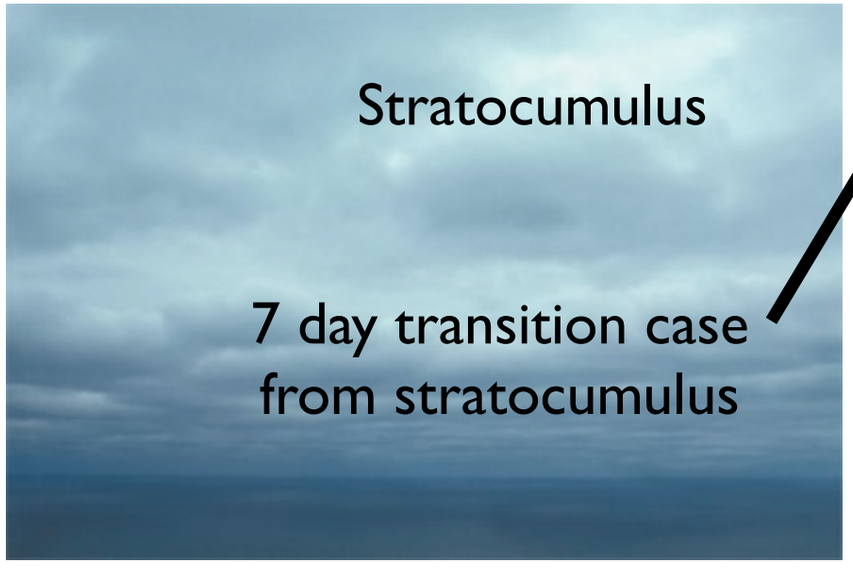
- To get a better idea of the performance of the various families of PDFs, use LES results.
- Compute
  - Cloud fraction
  - Cloud water
  - Liquid water flux

Calculate moments to specify PDF from LES for various horizontal grid sizes

LES Simulations

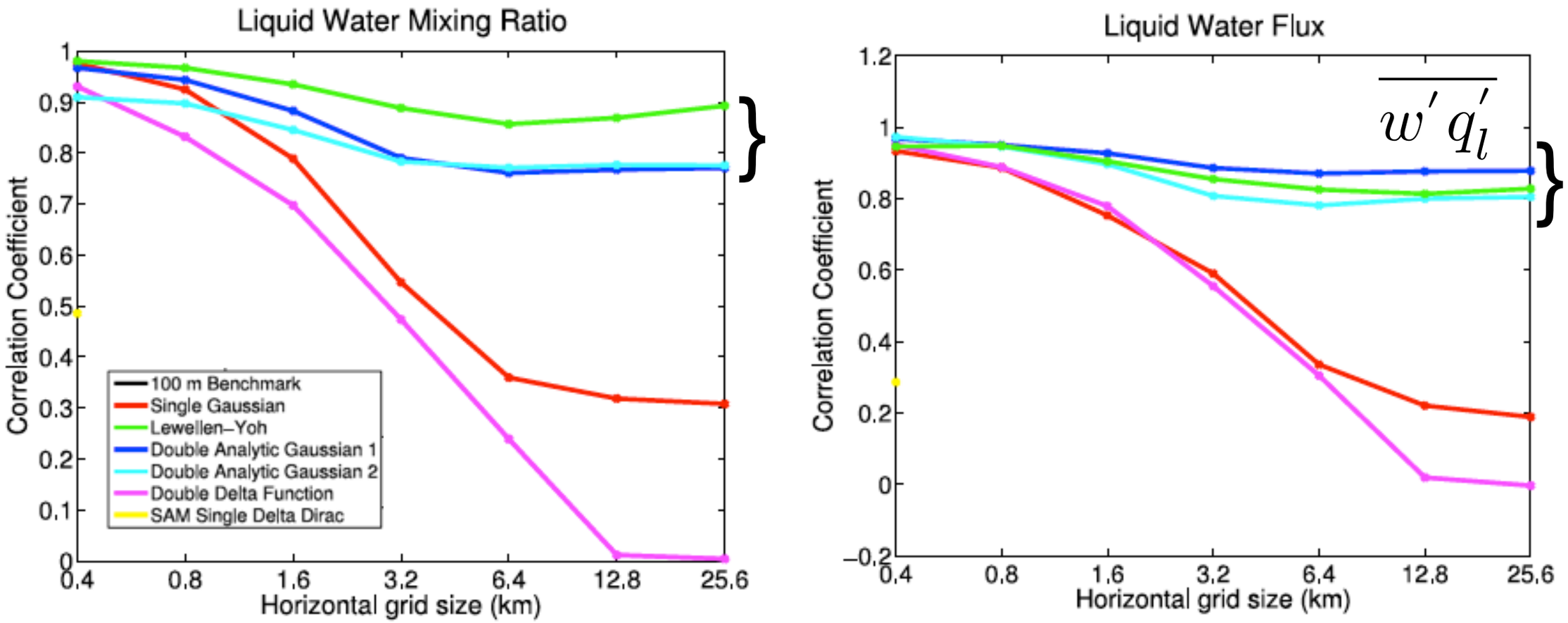
- Our (large domain) LES simulations used for *a priori* and *a posteriori* testing include:





Assumed PDF Method

A priori studies (Larson et al. 2002, Bogenschutz et al. 2010) show that *trivariate joint PDFs based on the double Gaussian shape* can represent shallow and deep convective regimes fairly well for a range CRM of grid box sizes.



From Bogenschutz et al. (2010), for BOMEX shallow cumulus regime

Assumed PDF Approach

$$\overline{\theta_l'^2}, \overline{q_t'^2}, \overline{w'^2}, \overline{w'\theta_l'}, \overline{w'q_t'}, \overline{q_t'\theta_l'}, \overline{w'^3}$$

- Typically requires the addition of several prognostic equations into model code (Golaz et al. 2002, Cheng and Xu 2006, 2008) to estimate the turbulence moments required to specify the PDF.

- Our approach is called *Simplified Higher-Order Closure* (SHOC):

  - Second-order moments diagnosed using simple formulations based on Redelsperger and Sommeria (1986) and Bechtold et al. (1995)

  - Third-order moment diagnosed using algebraic expression of Canuto et al. (2001)

  - All diagnostic expressions for the moments are a function of prognostic SGS TKE.

Turbulence Length Scale

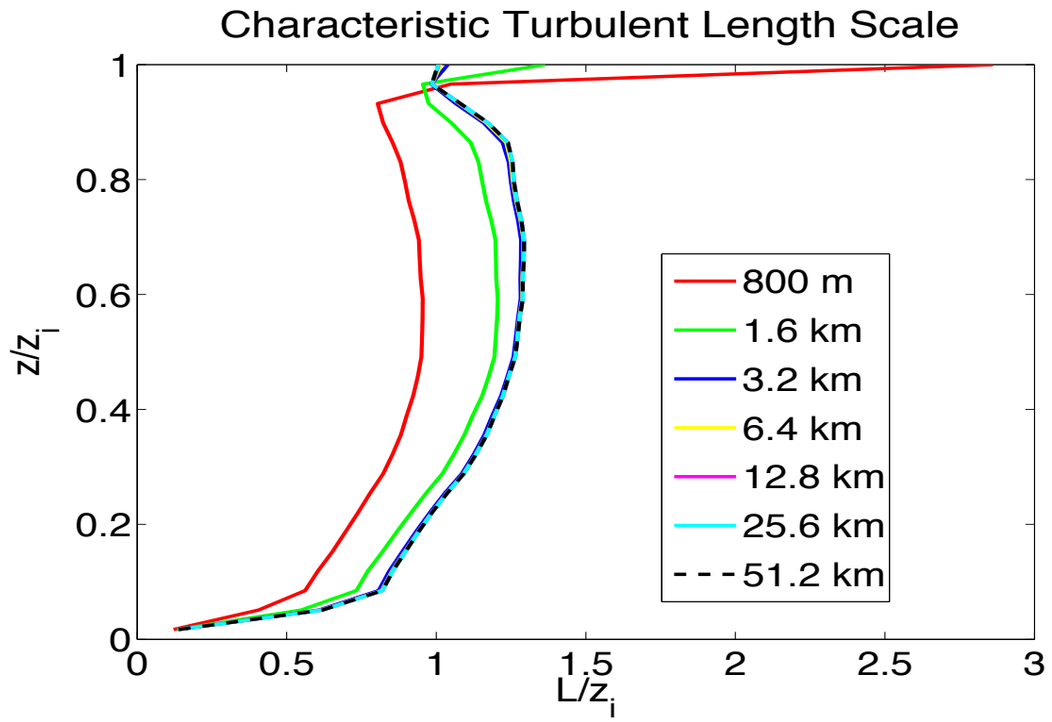
- Need to parameterize dissipation rate and eddy diffusivity:

$$\epsilon = \frac{\overline{e}^{3/2}}{L} \qquad\qquad K_H = 0.1 L \overline{e}^{1/2}$$

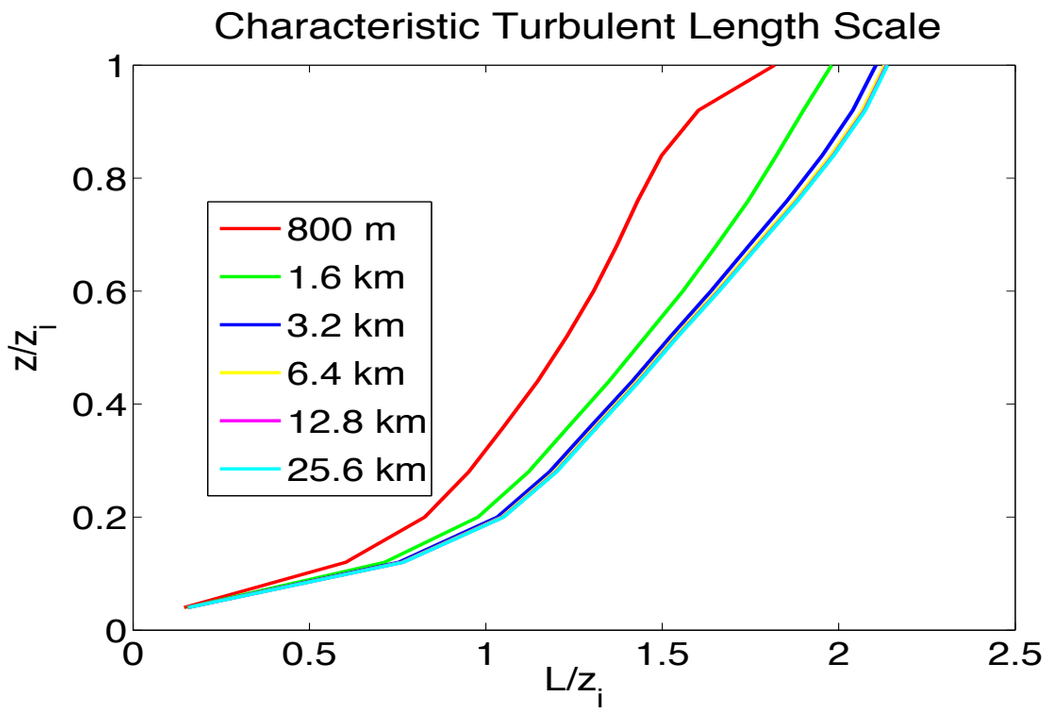
- Teixeira & Cheinet (2004) showed that $L = \tau\sqrt{e}$ works well for the convective boundary layer.

- We formulated a general turbulence length scale related to $\sqrt{e}$ and eddy length scales for the boundary layer or the cloud layer.

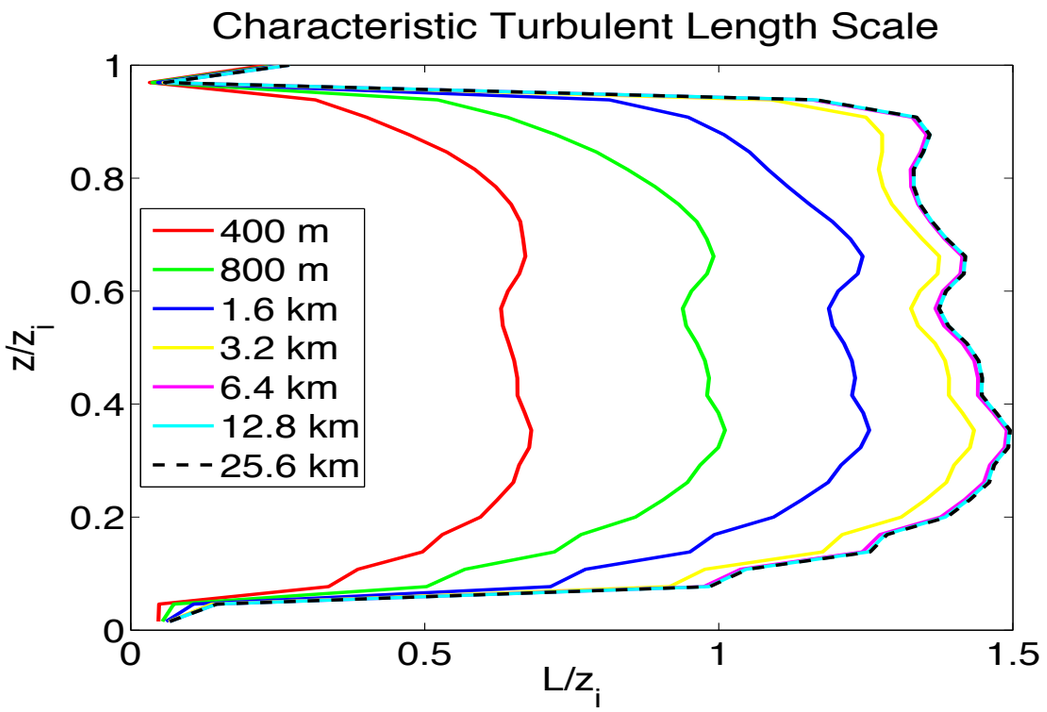
Turbulence length scale *diagnosed* from LES for various CRM grid sizes.



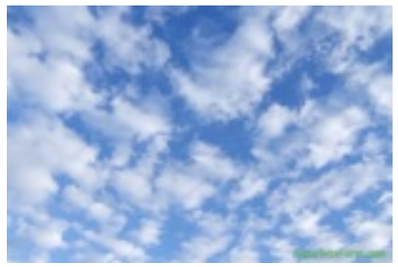
(a) Clear convective boundary layer



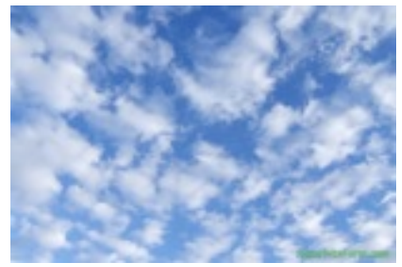
(b) Trade cumulus mixed layer



(c) Stratocumulus mixed layer



Standard SAM vs SAM-SHOC



SAM-SHOC incorporates our new turbulence closure model.

- **Standard SAM**
  - SGS TKE is prognosed.
  - Length scale is specified as dz (or less in stable grid boxes).
  - No SGS condensation.
  - SGS buoyancy flux is diagnosed from moist Brunt Vaisala frequency.

- **SAM-SHOC**
  - SGS TKE is prognosed.
  - Length scale is related to SGS TKE and eddy length scales.
  - SGS condensation is diagnosed from assumed joint PDF.
  - SGS buoyancy flux is diagnosed from assumed joint PDF.
  - Add'l moments req'd by PDF closure are diagnosed, so *no additional prognostic equations are needed.*

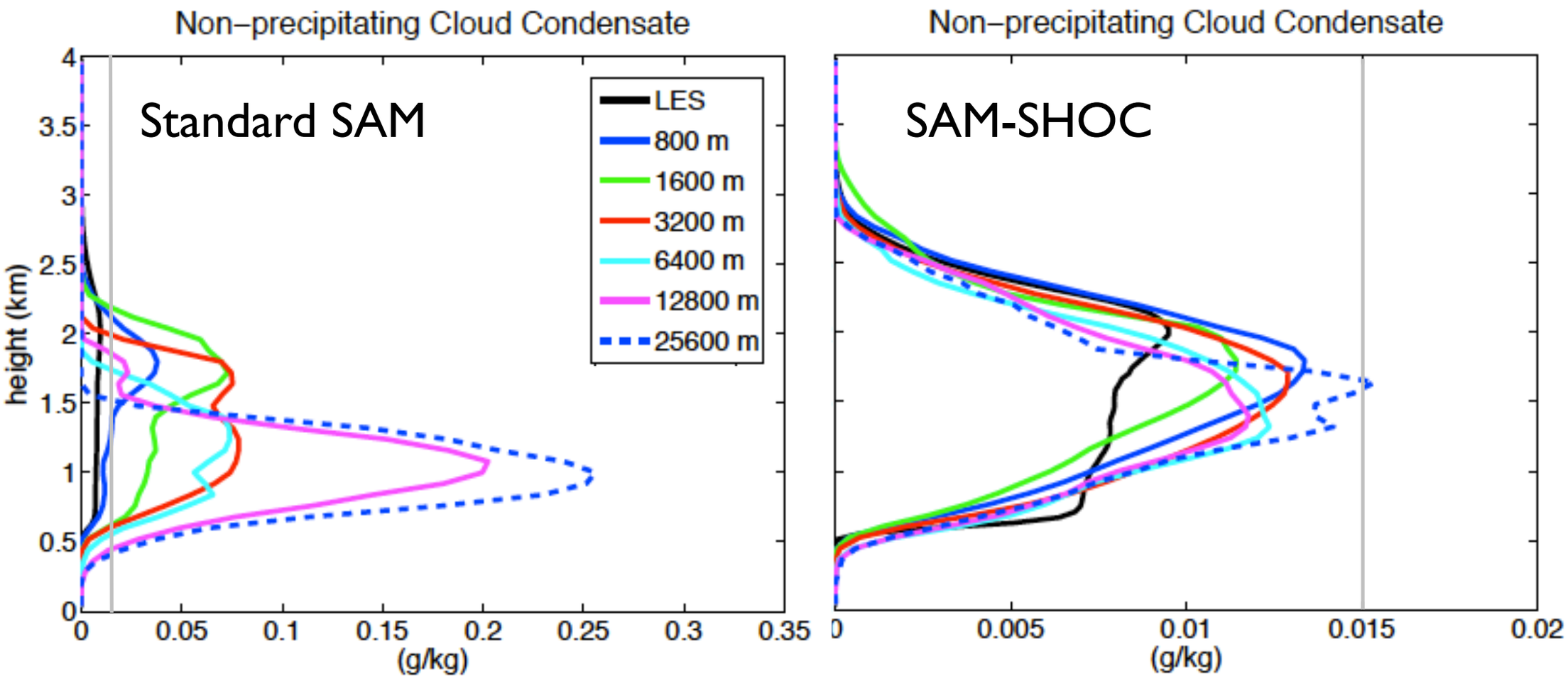
LES Benchmarks

- The following LES cases have been used to test SAM-SHOC in a 2D CRM configuration:

  - Clear convective boundary layer (Wangara)
  - Trade-wind cumulus (BOMEX)
  - **Precipitating cumulus (RICO)**
  - Continental cumulus (ARM)
  - **Stratocumulus to cumulus transition**
  - Deep convection (GATE) "Giga-LES"

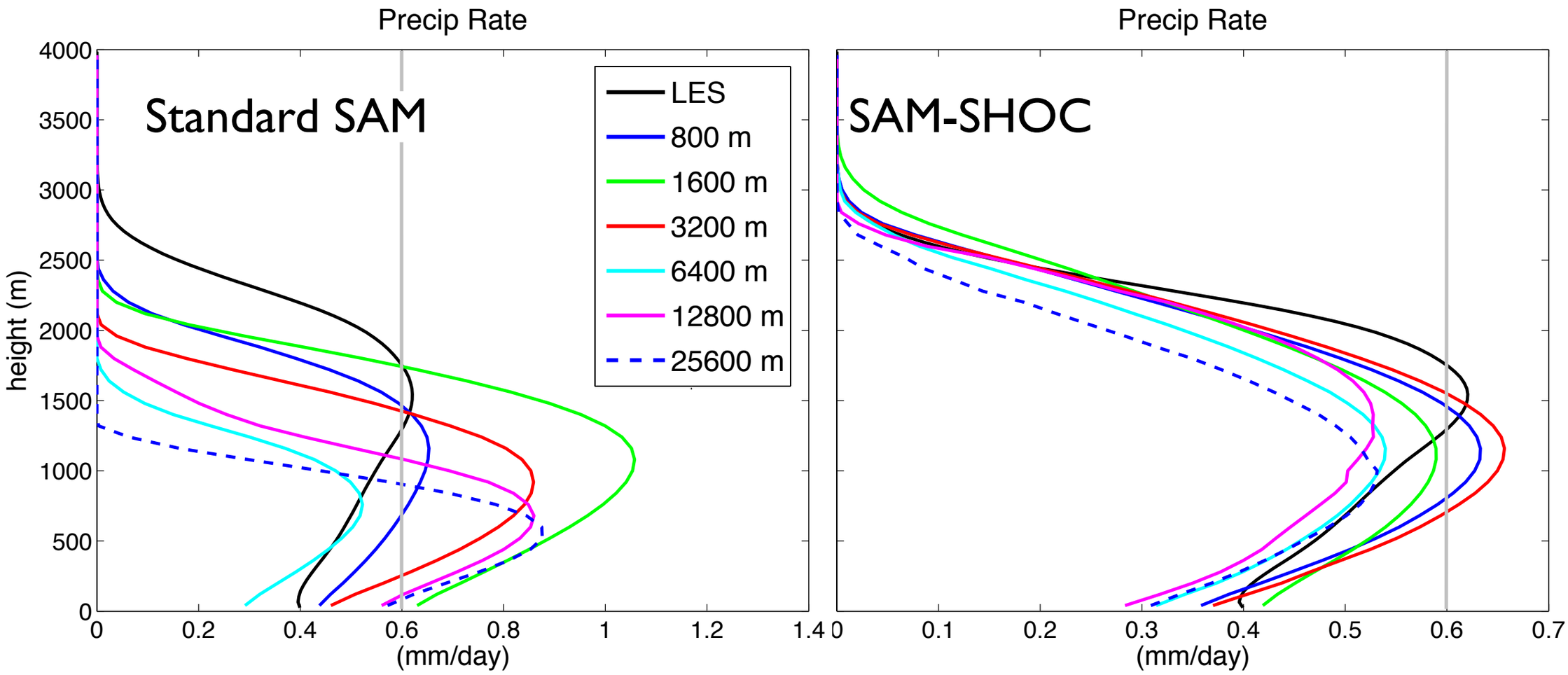
RICO: Precipitating Trade-Wind Cumulus

Dependence of Cloud Liquid Water on Horizontal Grid Size



RICO: Precipitating Trade-Wind Cumulus

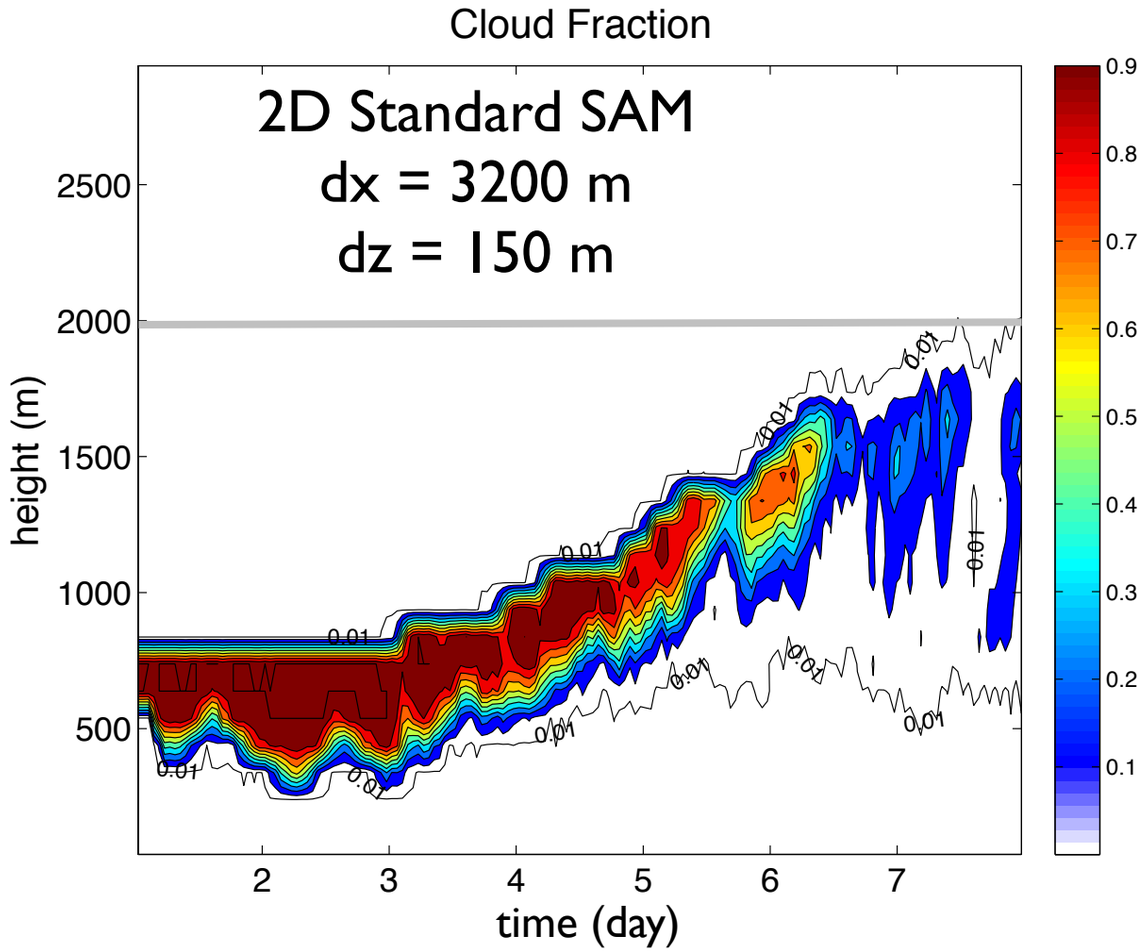
Dependence of Precipitation Rate on Horizontal Grid Size

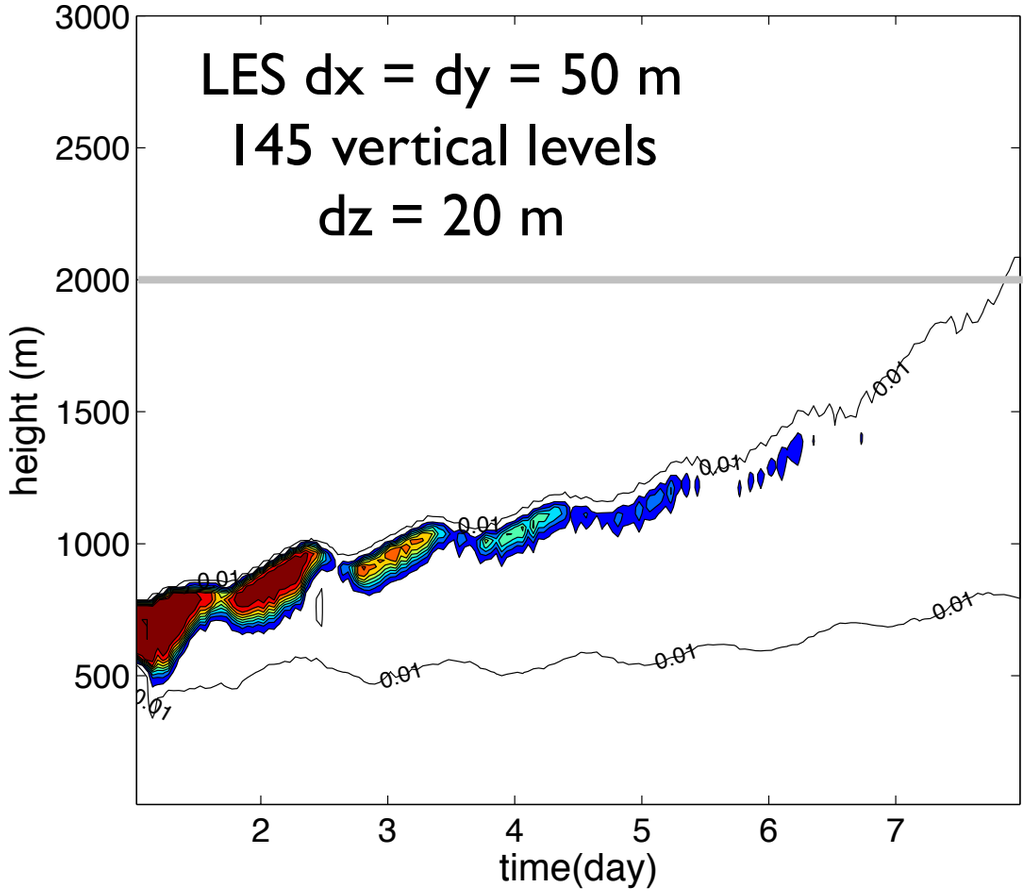


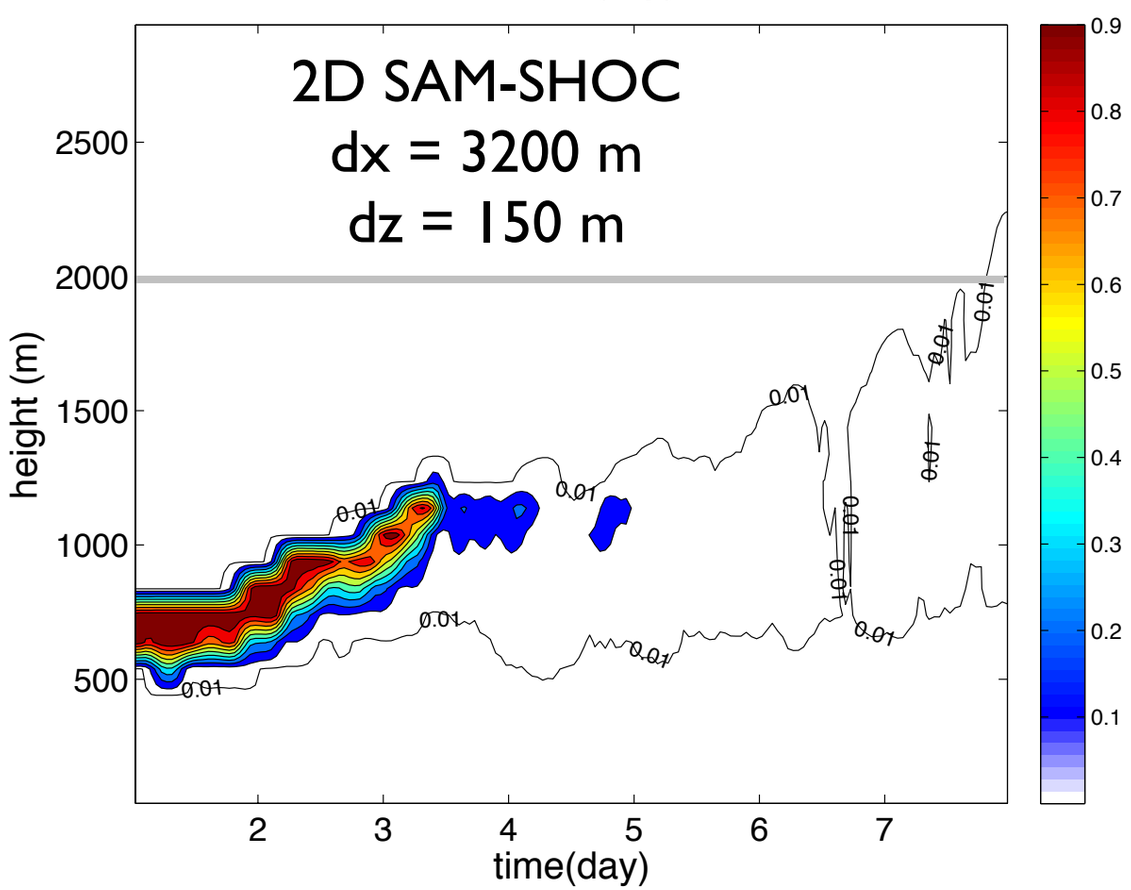
Observed surface precip rate was ~0.3 mm/day.

Lagrangian
Sc to Cu Transition Case

7 day simulation:
SST increases linearly.
Solar radiation varys diurnally.

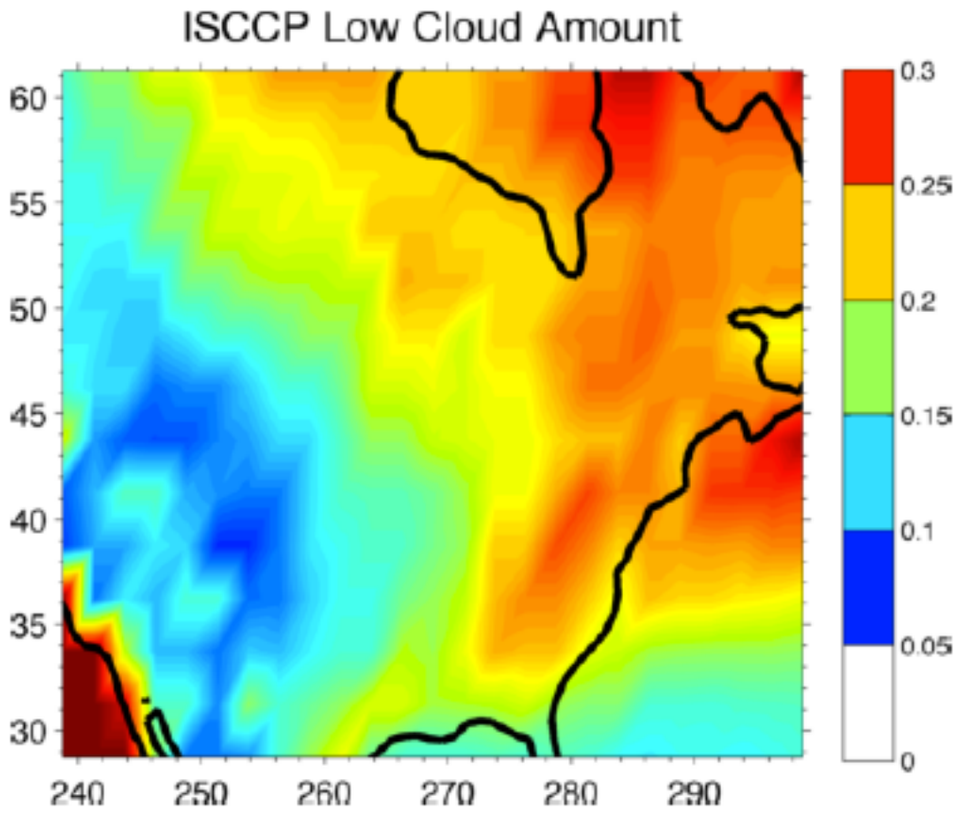




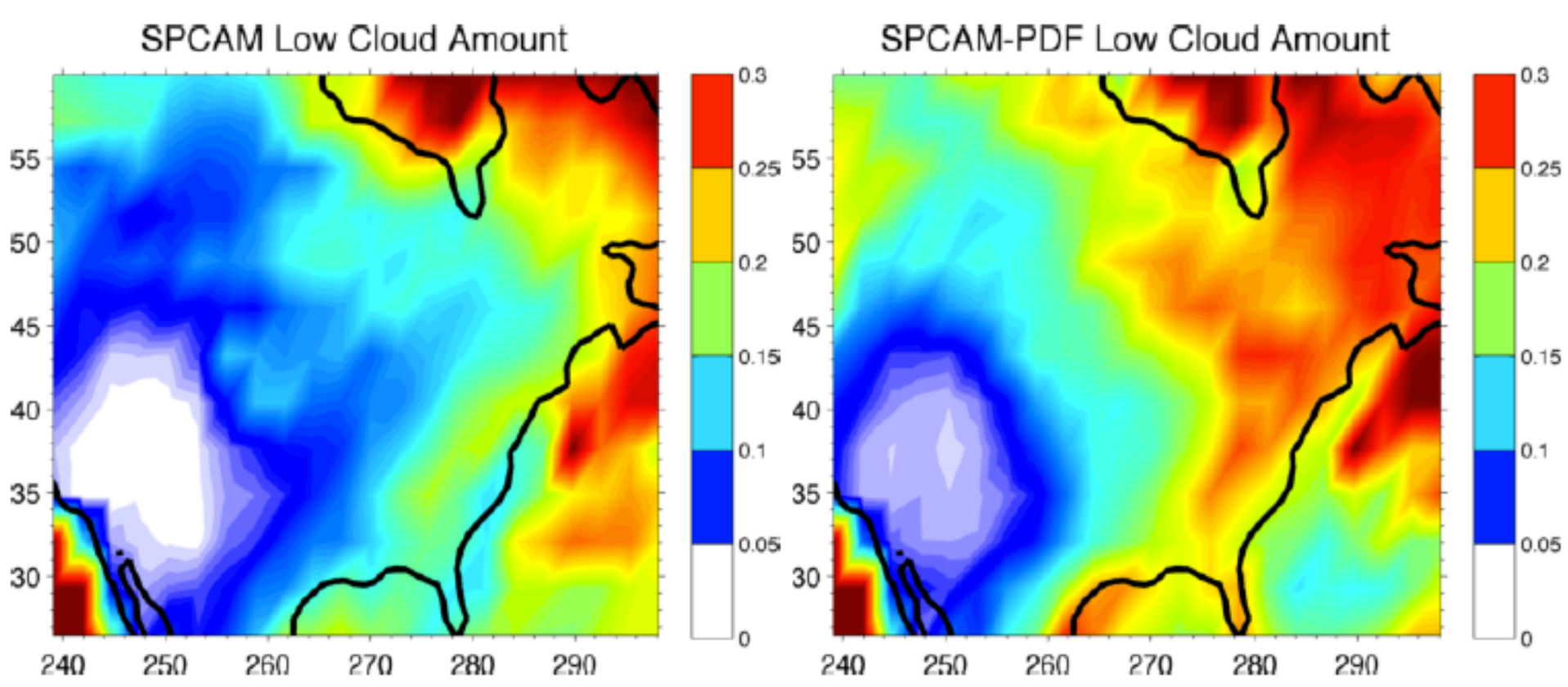


Preliminary Test of Closure within MMF

- Code implemented in the embedded CRMs within the MMF.
- Preliminary results are from June, July, August (JJA) simulation (with one month spin-up).
- SGS cloud fraction and liquid water content passed to radiation code (computed on the CRM grid every 15 minutes).
- SP-CAM & SP-CAM-PDF run in T42 configuration with 30 vertical levels (embedded CRM: dx = 4 km, dz ~ 200-300 m in boundary layer).



Low Clouds Over Land



Summary

- SHOC includes these desirable features:
  - A diagnostic higher-order closure with assumed double Gaussian joint PDF.
  - A turbulence length scale that depends on SGS TKE and large-eddy length scales.
  - It can represent many boundary layer cloud regimes in models with dx ~ 0.5 km or larger, with little dependence on horizontal grid size.
  - It is economical.

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Assumed Probability Density Functions for Shallow and Deep Convection

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A simplified PDF parameterization of subgrid-scale clouds and turbulence for cloud-resolving models

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